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Laboratory Calibration of Density-Dependent Lines in the EUV and Soft X-Ray Regions

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ABSTRACT

We analyzed spectral data of Fe XXII and Ar XIV from laboratory sources in which the electron density varies by several orders of magnitude to help benchmark density-sensitive emission lines useful for astrophysics and to test the atomic models underlying the diagnostic line ratios. We found excellent agreement for Fe XXII, but poorer agreement for Ar XIV.

1. Introduction

A number of astrophysically important emission lines are sensitive to electron density in the EUV and soft X-ray regions. Lines from Fe XXII, for example, have been used in recent years as diagnostics of stellar coronae, such as the active variable AB Dor, Capella, and EX Hya (Sanz-Forcada et al. 2003, Mewe et al. 2001, Mauche et al. 2003).

Here we report spectral data of Fe XXII and Ar XIV from laboratory sources in which the electron density is known from either K-shell density diagnostics (for electron beam ion traps) or from non-spectroscopic means (tokamaks), ranging from 5×10^{10} cm^{-3} to 5×10^{14} cm^{-3}. These measurements were used to test the atomic data underlying the density diagnostic line ratios, complementing earlier work (Chen et al. 2004).

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2. Methods

Spectra from the Livermore electron beam ion trap were taken with a varied-line-spacing flat-field grating spectrometer with a mean spacing of 1200 lines/mm and a CCD detector. Wavelength calibrations were periodically performed with higher orders of the well known K-Shell emission lines of N VI and N VII, commonly referred to as w and Lyman-α, respectively, and with lines of O V and O VI; see Lepson et al. (2002) for further details of spectrometer set-up and data acquisition. The electron density of the EBIT plasma was estimated via the ratio of the density-sensitive 1-2 N VI transition lines known as y and z (Chen et al. 2004).

Further measurements were taken with the same spectrometers, which were installed on the NSTX tokamak and christened "XEUS" for the lower wavelength instrument and "LoWEUS" for the higher wavelength instrument (Lepson et al. 2008, 2010). Wavelength calibrations were performed with higher orders of the C VI Lyman-α and C V w lines, as well as with O V and O VI, as on EBIT. The electron density of the plasma was measured directly with Multi-Point Thomson Scattering.

Measurements on the Alcator C-Mod tokamak at MIT were taken on a 2.2 m Rowland circle grating spectrometer with a micro-channel plate detector. Spectral resolution was lower than on EBIT and NSTX, but had time-resolution of 4–16 ms. Density was also measured with Multi-Point Thomson Scattering.

Observations of Capella (α Aurigae) were taken with the *Chandra X-Ray Observatory*'s Low Energy Transmission Grating Spectrometer. We used the minus order summed from several observations totalling $\sim$500 ksec.

We used the Flexible Atomic Code (Gu 2003, 2008) to calculate emission strengths of two boron-like line pairs in iron and argon known to be sensitive to the electron density. In iron, we examined the Fe XXII line pair $(2s2p^2)_{3/2} \rightarrow (2s^22p)_{3/2}$ at 114.44 Å and $(2s2p^2)_{1/2} \rightarrow (2s^22p)_{1/2}$ at 117.17 Å, which was also used by Mewe et al. (2001) as part of an analysis of the corona of Capella. For argon we examined the Ar XIV line pair $(2s^22d)_{3/2} \rightarrow (2s^22p)_{1/2}$ at 27.47 Å and the blend $(2s^23d)_{5/2} \rightarrow (2s^22p)_{3/2}$ and $(2s^23d)_{3/2} \rightarrow (2s^22p)_{3/2}$ at 27.63 Å.

3. Results and Discussion

Spectra of Fe XXII are shown in Figures 1 (a) – 1 (d) for EBIT-II, NSTX, and Alcator C-Mod. The change in relative line strength is obvious between the low- and high-density regimes.

Figure 2 shows the line ratio curve of boron-like density-sensitive lines calculated with

the Flexible Atomic Code for Fe XXII (a) and Ar XIV (b) and the ratios measured on EBIT-II, NSTX, and Alcator C-Mod (Chen et al. 2004, Lepson et al. 2010, Reinke et al. 2010). For Fe XXII, excellent agreement is found between theory and tokamak measurements near the high density limit. Agreement at lower density is not as good, but overlaps within the error limits. We are attempting measurements around the critical density of 10^{13} cm^{-3}, where the rate of change is greatest. For Ar XIV, agreement between theory and measurements is rather poor at both low and, especially, high densities, indicating the need for improved atomic models.
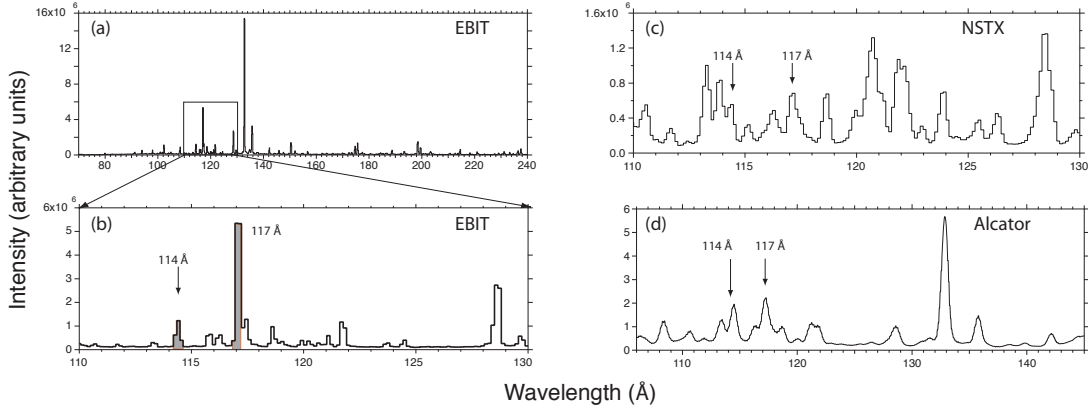

Fig. 1.— Spectra of iron from plasmas of different densities: (a) XEUS spectrometer at EBIT-II, with electron density $\sim 2 \times 10^{11}$ cm^{-3}. (b) inset showing the density-sensitive lines of B-like Fe XXII. (c) LoWEUS spectrometer on NSTX tokamak, where the electron density ranged from 9×10^{13} cm^{-3} to 1×10^{14} cm^{-3}. (d) Spectrum from Alcator C-Mod tokamak, where the electron density ranged from 9×10^{13} cm^{-3} to 5×10^{14} cm^{-3}.

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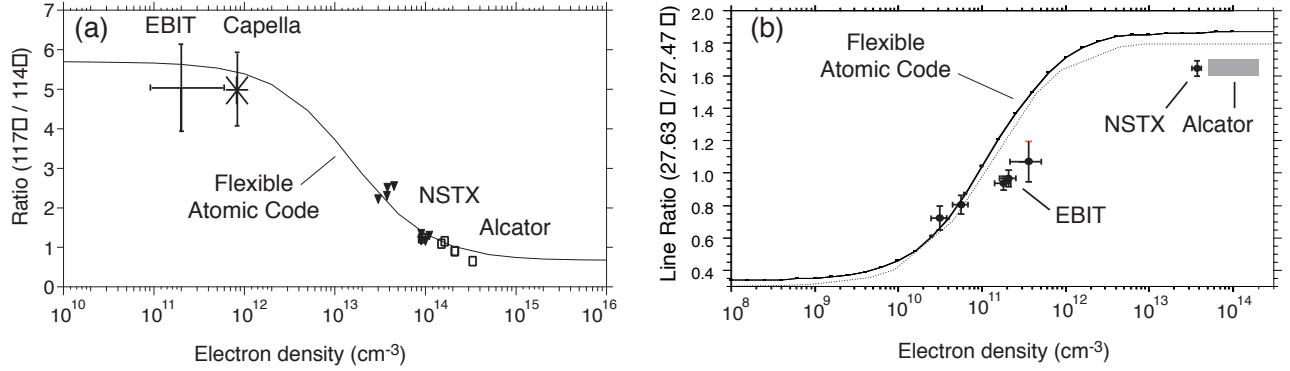
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Fig. 2.— Comparison of theory with measurements: (a) Ratio curve calculated for the boron-like Fe XXII line pair 117.17 Å / 114.44 Å. (b) Ratio curve calculated for the boron-like Ar XIV line pair 27.63 Å / 27.47 Å. Solid line is calculated for a Maxwellian distribution with electron energy of 0.3 keV for tokamaks; dotted line is calculated for monoenergetic beam with electron energy of 1.0 keV for EBITs.

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